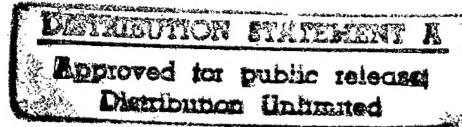


**A LITERATURE REVIEW OF METHODS TO DETERMINE
ROAD USER COSTS IN CONSTRUCTION ZONES**

BY

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CHAPTER 1 - INTRODUCTION

As freeway construction increases with the need to expand, repair and maintain the existing infrastructure, the desire to quantify the inconvenience or delay costs to the user of the freeway undergoing construction has increased and become necessary to assist in determining total project impact costs and determine penalties or lane rentals to contractors. This paper will review critical variables which impact delay costs, delay avoidance strategies and various methods and models developed to quantify these costs. Overall, the amount of research specifically in this area is limited as interest is just beginning to rise in quantifying these costs. However, numerous studies have been completed in the past in related areas which will be reviewed for their applicability to this project.

State Departments of Transportation need to determine impact costs to develop freeway projects in the most cost effective manner. The methods used in project sequencing, scheduling, and work hours must provide the least impact to the traveling public without incurring excessive costs to the project. Businesses which rely on freeways to deliver their goods and services can be particularly impacted. The inability to deliver goods and services on time begins to have significant impacts in this era where more companies are shifting to "just-in-time" delivery methods to reduce costs, particularly inventory storage costs. Companies with perishable goods are also at significant risk if these goods cannot be delivered to consumers with sufficient shelf life remaining.

Freeway users not involved in business are also impacted by construction delays.

While these costs are much more difficult to quantify, the user definitely experiences frustration and a sense that time is being wasted while waiting to bypass constricted areas on the freeway.

CHAPTER 2 - VARIABLES AFFECTING DELAYS

In order to develop an accurate model, it is first necessary to identify the variables which will or can have an effect on the amount of delay. While this is not intended to be all inclusive, the variables discussed are considered in the literature reviewed for this report. The most critical and encompassing are capacity and actual traffic volume. For the most part, all other variables can be linked or considered a component of these two areas.

CAPACITY

Freeway capacity is defined as the maximum number of vehicles per time period a freeway can handle within a given roadway section. Travel speed is directly related to capacity since as speed increases, more vehicles can traverse the construction zone. The actual capacity within a construction zone is affected by several variables. The most obvious is the number of lanes available for through traffic in relation to the number normally available. This is expressed by stating the lanes available prior to construction followed by the number of lanes available in the construction zone (e.g., two to one, two lanes reduced to one lane in the construction zone). Reductions in the number of available lanes require traffic to merge out of lanes being closed and into open lanes.

Placement of advance warning signs impacts capacity by alerting drivers of upcoming obstructions. With proper warning, drivers will adjust their behavior by changing lanes, if necessary, and being more alert to permit more efficient flow and higher speeds through the construction zone.

dition affects capacity by influencing the speed which drivers will construction zone. Pavement Serviceability Rating (PSR) is a subjective smoothness of the roadway. Often in construction zones, ve more bumps and unevenness resulting in a lower PSR and hence dition to the PSR, weather can make the roadway wet or icy further

icing the detour for the

for more through lanes

i. This becomes more

behavior resulting in

: safety reasons and to
barriers can result in
in size and composition
cones have less effect
relocate them

the construction zone can
where traffic is detoured
often insufficient for
entering or exiting to use
forces through traffic to

v. Vehicle breakdowns

construction zone, breakdowns and accidents are compounded by the often lacking of an emergency lane or shoulder area in which disabled vehicle(s) can be relocated. The same lack of road shoulders also prevents assistance (emergency vehicles and/or tow trucks) from reaching the incident site. The occurrence of a random incidence being related to or caused by the construction must be verifiable. One would need to show a clear indication that the frequency of these random events occurring within a construction zone is higher than in non-construction zone. A connection is much more likely when incidents occur during periods when traffic flow exceeds capacity resulting in the formation of queues.

The final factor in determining capacity is the curvature and grade of the roadway. Both items can limit the sight distance of drivers. Most often in urban areas, right of way constraints can require sharper curves which reduce the safe unconstrained speed (normal highway speed limit) to lower limits. Grades, particularly for larger, heavier vehicles, will change the acceleration and deceleration rates. Not only do curves and grades result in slower speeds, but also greater distances between vehicles as drivers (particularly trucks) try to allow sufficient space to maneuver to avoid being involved in an accident.

TRAFFIC VOLUME

Traffic volume is defined as the actual traffic flow measured in number of vehicles per time period. The Highway Capacity Manual (1994), in this instance (as well as for capacity), designates the automobile as the standard vehicle. Larger vehicles such as trucks are given an adjustment factor based on type to convert the actual number to a standardized number of automobiles.

Time of day affects the amount of traffic on the freeway. The most obvious is in urban areas where the morning and evening rush hours result in peak traffic loads. Even in rural areas, traffic volume changes throughout the day. Most noticeably, are the differences between night and day.

The percentage of larger, heavier trucks affects the traffic flow. During unconstrained (non-construction) freeway zones, large trucks will generally travel at speeds comparable to the standard automobile. However, within construction zones and congested areas, truck drivers will travel at slower speeds due to the longer stopping distance and lower acceleration rate of their vehicles. The effect of the slower truck speed on the entire traffic stream is to reduce the total speed of all vehicles. Automobile drivers will be forced to travel at the same speed if in the same lane until they can accelerate and merge into other lanes to pass the slower moving trucks. For automobiles not in the truck's lane, the drivers are forced to slow to allow vehicles to merge from the lane with the truck.

CHAPTER 3 - PREPLANNING AND TRAFFIC MANAGEMENT PLANS

Preplanning is a key ingredient in reducing excess user costs during road construction projects. In this chapter, a review is made of several traffic management planning studies. The studies include all-encompassing efforts during a major urban reconstruction project to simple methods to improve sign placement and increase the number of open lanes. Traffic engineers must plan and execute projects with an effort to mitigate impact costs to the user. A comprehensive corridor traffic management plan can significantly reduce user costs, reduce the public frustration during delays, improve the public relations and image of the agency undertaking the project, and lead to long term benefits of increased use of mass transit alternatives in urban areas.

USE OF FREEWAY SHOULDERS AS TRAVEL LANES

Freeway capacity can be increased significantly by using road shoulders as travel lanes. Though not used as a specific example in his article, William C. McCasland in Impact of Using Freeway Shoulders as Travel Lanes on Fuel Consumption specifically mentions the ability to use the freeway shoulder to restore a portion of the capacity lost during lane closures. The following example clearly shows the increase in capacity and decrease in delay available by utilizing this method.

Utilizing the shoulder increased the number of lanes from four to five for one-third of a mile prior to the first high use exit ramp and from three lanes to four for the following one-third mile which was prior to the second high use exit ramp. The additional lane

increased the calculated maximum freeway capacity by 22 percent. Measuring from two miles upstream of the first exit ramp, the average speed for three miles increased from 20 mph to 40 mph thereby decreasing the travel time through the congested area by half.¹

TRAFFIC CONTROL DEVICE CONSIDERATIONS

Two studies reviewed indicate the importance of placement location and types of traffic control devices can have on improving traffic flow. In each study, the objective was to influence driver behavior to merge out of the lane to be closed and into the open lane prior to the actual taper (lane closing). If successful, fewer vehicles would become "trapped" at the taper requiring a significant reduction in speed including stopping followed by attempts to merge with high-speed traffic traveling in the open lane. The result would be lower risk of accidents and less deceleration and subsequent acceleration by all vehicles.

The first study, Sight-Distance Requirements at Lane-Closure Work Zones on Urban Freeways conducted by Stephen H. Richards and Conrad L. Dudek consisted of a preliminary field study followed by a controlled field study. The definition of "sight distance" is the distance at which the drivers can actually see the lane closure or taper. In both cases, a vehicle was considered "trapped" if it was in the lane to be closed within a distance of 200 feet of the start of the taper. For the preliminary field study, 14 work

¹ McCasland, William R., "Impact of Using Freeway Shoulders as Travel Lanes on Fuel Consumption", Transportation Research Record, Issue 901, YR, pp. 1-5.

zones were observed and data collected used. The sight distances varied from a high of 5100 feet to a low of 600 feet. The results indicate that for sight distances in excess of 1500 feet, less than 20 percent of the traffic in the closing lane upstream was "trapped" at the taper. As the sight distance was reduced to between 1000 and 1500 feet, the percent of vehicles trapped increased slightly to 20 to 25 percent. As the sight distance dropped below 1000 feet, "trapped" vehicles increased sharply to between 65 and 80 percent.

During the controlled field study, a four-step process was used to collect data at work sites with lane closures. The site selected included a hill which prevented drivers from seeing the actual taper area. The approach signs were placed upstream of the hill to warn drivers of the upcoming lane closure. First, data were collected during free traffic flow, prior to sign erection and work commencing. Second, data were collected with approach signs erected from 2100 feet to 5100 feet prior to the planned taper but without actual lane closure to determine the effectiveness of the approach signs. Third, data were collected with the lane closed utilizing plastic cones for the taper and a static arrow sign at sight distance of 900 feet and 1600 feet. Fourth, the static arrow sign was replaced by a flashing arrow sign to attract more attention with data again collected under sight conditions of 900 feet and 1600 feet.

Results of the data collected indicate that only 39 percent of all drivers moved out of the closing lane during step two (approach signs present, but no lane closure) as measured at 2000 feet past the last approach sign. Additionally, when compared to traffic volumes, drivers were more likely to change lanes under less traffic (47 percent at 1000 vehicles per hour and 23 percent at 3000 vehicles per hour). Once vehicles crested the hill

and drivers saw the lane was not closed, they quickly began returning to the lane slated for closure. Based on these results it is evident that many drivers will not initiate a lane change until they can verify the lane is actually closed especially when traffic is heavy. In both steps three and four, increased sight distance encouraged drivers changing lanes sooner even though the number of vehicles "trapped" were the same. In comparing the effect of the flashing arrow to the static sign (results between steps three and four), the flashing arrow had little effect at the sight distance of 900 feet. At 1600 feet, drivers significantly changed lanes sooner.²

The results of this study clearly show that increased sight distance and signs which attract more attention improve driver response to closed lanes. The flashing arrow has now become the standard for lane closures.

The second study, Evaluation of I-75 Lane Closures by Jerry G. Pigman and Kenneth R. Agent, evaluates the effects of additional traffic control devices in addition to the minimum requirements set forth in the Manual on Uniform Traffic Control Devices on driver behavior at lane closures. The additional devices used included variable message signs, supplemental signs, and rumble strips. The variable message sign was a flashing sign alternating between the statement "Merge Right" (or Left as appropriate) and an arrow placed between .9 and 1.8 miles from the taper depending on sight distance requirements for the sign. The supplemental signs were construction zone signs placed at

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Richards, Stephen H. and Conrad L. Dudek, "Sight-Distance Requirements at Lane-Closure Work Zones on Urban Freeways", Transportation Research Record, Issue 864, YR, pp. 14-20.

5, 4, 3, and 2 miles before the lane closures. The rumble strips consisted of five sets placed at 1.5, 1.0, 0.6, 0.3, and 0.1 miles before the taper. Each set consisted of eight strips spaced two feet apart. The standard devices used throughout the study began at one mile from the lane closure.

Like the previous study, data were collected before the addition of any additional device and between each addition of the next listed device. The data collection points were before the construction zone signs to determine the free flowing traffic state prior to driver awareness of an approaching construction zone, at the variable sign location (or where it would be placed), between the variable message sign and the taper, and at the beginning of the taper. Because of changes in location of the work zone sites during different phases of this study, the geometric effects of each individual site made evaluation of the data more complicated.³

A review of the data clearly shows a steady decrease in the percentage of traffic in the closed lane as each supplemental device was added. Even though the rumble strips were added beginning 1.5 miles from the taper and resulted in the lowest percentage of "trapped" vehicles, their effect did not manifest itself until after the vehicle passed the 0.8 mile observation point.

A review of the northbound data shows approximately 60 to 65 percent of the traffic travels in the right lane. When this lane is the one closed, a higher percentage of

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Pigman, Jerry G. and Kenneth R. Agent, "Evaluation of I-75 Lane Closures", Transportation Research Record, Issue 1163, 1988, pp. 22-30.

vehicles will become "trapped" at the taper. The cause is probably attributed to the greater number of vehicles that must merge left and that the drivers in the right lane normally travel at lower speeds and are unwilling to accelerate to merge into the faster moving traffic of the left lane. Instead, they will remain in the right lane until sufficient space is available to merge right.

Overall, both studies show the strong need to preplan the placement of traffic control devices to ensure adequate sight distance with respect to the geometric configuration of the freeway at the work zone. Further, the use of supplemental traffic control devices should be considered to influence driver behavior to merge sooner and provide a smoother traffic flow.

COMPREHENSIVE TRAFFIC MANAGEMENT

Particularly in urban areas, a comprehensive traffic management plan is essential to maintain a smooth flow of traffic through construction zones. The high volume of traffic, particularly during peak periods, can quickly result in long delays. This section reviews two such plans, the first a freeway bridge resurfacing project and the second, a major reconstruction of a freeway over a two-year period.

Plan One: Traffic Impacts of Bridge Resurfacing on Northbound Interstate 5 Through Seattle

In his report, Traffic Impacts of Bridge Resurfacing on Northbound Interstate 5 Through Seattle, John Mieras describes the traffic management plans implemented and their success rate at reducing delays caused by the resurfacing project. The bridge to be

resurfaced was a primary corridor for commuter traffic. In fact, it was one of six routes available to cross the Washington Ship Canal. The project consisted of three phases. The first was bridge deck preparation which included grinding and joint repair. The second, consisted of final cleaning (sand blasting) and placement of the new surface. And third, was a final cleanup of the project site. The traffic management plan consisted of two phases, one during the deck preparation phase and the second during sand blasting, overlay placement, and cleanup.

The first phase of the plan scheduled all preparatory work to be conducted from 8:00 p.m. to 6:30 a.m. on weekdays and on weekends when traffic would be lightest. High noise activities were further restricted to end by 11:00 p.m. Throughout this phase all lanes were open during the heavy daylight traffic hours but the surface condition was so poor that speeds were significantly reduced.

In the second phase, a temporary median would be erected permitting the complete closure of two out of four lanes during sandblasting and resurfacing operations. Further, the remaining lanes would be reduced from 12 foot widths with 6 foot shoulders to 11 foot widths and limited shoulders. Capacity was expected to drop 60 percent from 7600 vehicles per hour to 3000 vehicles per hour. To provide more capacity, the plan incorporated the use of the HOV express lanes for northbound traffic for the majority (20 hours) of the day and 24 hours per day on weekends. The weekday morning rush period from 5:30 a.m. to 9:30 a.m. was the only exception. Finally, to encourage the use of mass transit or car-pooling, two of the downtown exits were designated for HOV use only.

In addition to the changes in the traffic patterns, the following planned and coordinated efforts were made throughout the project to mitigate the delays of travelers. Metro Transit (city bus service) staged backup coaches downtown which could be used in case buses were delayed on the return trip of their route. This helped to keep the downtown departing routes on time. Metro Transit also added three additional routes to offer more alternative transportation methods and were able to use the HOV designated exit ramps.

The Metro Commuter Pool (car pool coordination office) increased distribution of car pooling information. Targeted areas were those expected to be most impacted by the resurfacing project. Distribution began prior to the start of the project.

Seattle Engineering and Washington State Department of Transportation (WSDOT) retimed signals within the effected area and along the major alternate routes through the corridor. Additionally, any short term road maintenance planned during the resurfacing project was rescheduled to other times and only emergency tasks were done.

Seattle Police and Washington State Patrol provided officers to assist with traffic control at critical points and times at the project site, alternate routes, and within the effected area.

WSDOT operates five low power radio stations and maintains radio contact with local radio station "sky pilots" which were used to convey current information on traffic congestion and best choice of alternate routes. Through use of its Closed Circuit TV system to monitor freeway traffic, WSDOT was able to provide near real time information and identify problems quickly. As part of the contract requirements, the

construction contractor had to stage a tow truck near the project for quick dispatch during peak traffic hours.

The results of the coordinated effort were generally successful particularly in the reduction of traffic through the construction zones on high demand weekdays. No severe congestion was reported during the project on any of the alternate routes. The total reduction in vehicles amounted to 32,200 per day. Of this number, 12,900 chose the HOV express lanes as an alternate route while only 1000 drivers chose to use I-90 east to I-405 as an alternate route. SR 520 traffic count decreased by 6,500 which was expected since it had the two main entry/exit ramps that were converted to HOV only. The remaining trips can only be attributed as discretionary trips that were not undertaken as a result of the public information campaign conducted before and during the project. The success of the public information plan was credited with most of the traffic reductions and congestion avoidance.

The Commuter Pool did see a sharp increase of 33 percent and 47 percent in ride-match calls per month over the prior year during the two-month project. The only disappointment was with Metro Transit. The three new bus routes garnered ridership numbering only 50 people per day, primarily on two routes prompting the bus service to cancel one route. Also, ridership on exiting routes did not show any appreciable increase.⁴

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Mieras, H. John, "Traffic Impacts of Bridge Resurfacing on Northbound Interstate 5 Through Seattle", ITE Journal, March 1986, pp. 29-31.

Plan Two: Southeast Expressway Reconstruction Project

The second plan reviewed was a highly comprehensive plan and study of the Southeast Expressway Reconstruction Project in Boston, Massachusetts. The scope of the project was the complete reconstruction of an 8-lane, 8.3 mile segment of I-93 which is the primary corridor from Boston to southeastern regions (suburbs) of Massachusetts. The freeway consisted of 15 bridges which would be rehabilitated, resurfacing of the entire length, widening of the right of way to improve merging areas, breakdown pullout areas, and a strengthened shoulder lane which could be used as a temporary lane during peak demands. Additional items included redesigned and improved drainage and signing schemes.

Because of the high visibility of the project and its very disruptive nature and impact on the metropolitan area, the state legislature was involved in reviewing the project and budgeted \$2 million to fund the implementation costs of the traffic management plan. In the end, nearly \$10 million was spent on various actions. Nearly any action which was deemed likely to help reduce the traffic volume while maintaining the flow of people was utilized and was studied to determine the benefits gained.

The primary area of concern was within the construction zone. Included in the contract was the construction schedule which limited the contractor to closing only two lanes at one time with half of the lanes completed the first year and the remaining during the second year of the project. Jersey barriers were required to separate each side of the freeway in half, effectively dividing the freeway into four two-lane sections. Of the three sections available during reconstruction, the center section was used as reversible express

lanes for through traffic. Further, trucks were prohibited from using the reversible express lanes. The configuration worked better than expected as weaving and lane changes across all lanes was limited. Consequently the bottlenecks which often develop around entry and exit ramps was reduced significantly. An added benefit was the reduction in accident frequency from preconstruction data.

Additional contract requirements were round-the-clock staging of tow trucks to deal with disabled vehicles, a continuous police presence for traffic management and emergencies, establishment of a project traffic control management center, proper advance warning signs to direct traffic to the proper available lanes, and the erection of screens at work sites to prevent motorist distraction with work site activity. As in incentive/disincentive, the contract included a \$10,000 bonus for each day the contractor completed the project ahead of schedule with the same amount assessed as liquidated damages for each day the contractor was late. Due to this contractual requirements and the impact they had on the schedule, the contractor was included as a team member in establishing the traffic management plan.

The enhancements made to the construction zone, coupled with the public relations program resulted in the redirection of more than 9000 vehicles from the expressway the first year from 6:00 a.m. to 7:00 p.m.. Despite the reduction in the number of lanes available by 25 percent, the configuration employed resulted in a decrease in travel time. By the second year, traffic volumes returned to their preconstruction levels as did the travel times with the exception of the southbound evening rush hour which increased.

Activities outside the construction zone concentrated on encouraging and providing alternative transportation means to reduce the number of vehicles required to use the freeway. Strong efforts were focused on expanding the available service for alternative modes of transportation and also improving the convenience to use these alternative modes.

Public relations efforts through regular news releases, monthly bulletins, and brochures strongly promoted the use of alternate modes of transportation, a variable work hour program for downtown employers, and a commuter information clearing house operated through a nonprofit organization.

Commuter rail capacity was increased by 2100 seats during rush hour and service frequency increased to effected areas. As the most expensive part of the corridor management plan, the rail service underwent a two-year \$3.6 million dollar improvement project on the four lines servicing the most area affected by the reconstruction project. Based on actual boardings, the number of passengers utilizing the rail service increased by 367, an 11.5 percent increase. Simple arithmetic shows that more than \$10,000 was spent in improving rail service for each passenger gained, a disappointing result. On the plus side, the commuter rail survey responses indicate that 95 percent of the new riders were previously drive alone expressway commuters and would continue to use the rail service even after the completion of the reconstruction project.

Commuter boat service increased its frequency as well as expanded service to new areas. Unfortunately, data is insufficient to determine an increase related to the reconstruction project.

Bus service, both public and private, was expanded in 27 communities through the addition of 1,200 new one-way trips primarily on existing routes. Unfortunately, ridership increases did not materialize and initially decreased by 4.5 percent. The companies soon dropped the additional routes added and ridership did return to preconstruction levels.

New coordination between public/private ventures to encourage inter-modal use of all transportation methods. Private bus and boat operators were permitted to sell monthly passes for publicly-owned service at a 20 percent discount. Park and Ride lots were expanded through new construction, re-striping, and leases to add 1500 new spaces. Unfortunately, these added benefits failed to attract new riders.

Finally, improvements were made on four routes identified as alternative corridors which could expect to see an increase in volume by those people who still drove but sought out alternative routes. Key congestion points were identified and planning was conducted with local officials. Signal and pavement marking changes were made to 29 intersections to improve traffic flow. In an innovative step, \$500,000 was provided to these local communities as freeway reconstruction impact aid. Based on demonstrated impacts and needs, the local communities were able to fund additional police and emergency response personnel during peak periods to shorten the time required to clear alternate routes from disabled vehicles. During the first year of the reconstruction project vehicle volumes increased by more than 9000. Due to improvements made, actual commuting time actually decreased on these routes from the preconstruction levels.

During the second year, no data were collected on volume though travel times did increase suggesting an increase in volume from the first year.⁵

Additional Considerations

In Freeway Incidents and Special Events: Scope of the Problem, Conrad L. Dudek examines the problem in general and recommends preplanning in traffic management to minimize the impacts of these occurrences. While not written toward construction work zones in particular, he emphasized the need for planning in incident detection and incident response (which includes response time and type). Many of the methods recommended for incident detection were utilized in the previous plans.

Additional methods not covered include emergency call boxes or telephones, cooperative motorist aid systems, CB radio, and patrol (including non-police) vehicles.⁶

One final traffic management plan concerns the Central Artery/Tunnel Project currently ongoing in Boston.⁷ The effectiveness of the plan will not be fully realized until after completion of the project, however, some notable considerations have already taken

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Steffins, William T., Sonia Weinstock, and Mary Ellen Sullivan, Corridor Transportation Management for Highway Reconstruction: Southeast Expressway, Massachusetts 1984-1985, U.S. Department of Transportation, Washington DC, 1986.

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Dudek, Conrad L., "Freeway Incidents and Special Events: Scope of the Problem", Transportation Research Circular, Issue No. 326, 1987, pp. 5-12.

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Cutler, Mark R., "Use of Traffic Forecasting Models in the Development of Traffic Management Plans for Construction of the Central Artery/Tunnel Project", Transportation Research Record, Issue 1404, 1993, pp. 8-14.

place. First, the construction schedule which was developed prior to that of the traffic management plan required an extensive rework to mitigate the congestion that would have been caused. Second, the inclusion of environmental considerations in the traffic management plan, specifically air quality standards, is a new area that must be addressed particularly in urban areas.

CHAPTER 4 - DELAY MODELS

This chapter will review three models developed to estimate delays within the work zone. The models were evaluated against actual data by Dr. Karen Dixon and Dr. Joseph Hummer whose methods and results are summarized here. The focus of analysis was the queue condition.

In theory, the minimum travel time is the time necessary to travel a section of road during a zero-flow condition. In reality, this translates to a single vehicle traversing a stretch of road with no obstructions where the driver can proceed at the maximum safe speed consistent with applicable speed limits and geometrics of the roadway. Unfortunately, roads must be shared with other drivers and as volume increases delays will be incurred. In conditions with no obstructions and low volume of traffic, the delay is too minimal to consider. However, as demand increases to and exceeds capacity, or obstructions (such as work zones) reduce capacity to at or less than the demand, delays will occur.

Most drivers will slow down when entering a construction zone. During low traffic volume conditions, little impact is incurred from surrounding vehicles. The only impact is to obey the speed limit signs (if the driver so chooses) requiring reduced speeds in construction zones. In their study, Drs. Dixon and Hummer ignore these small speed fluctuations and consider only the delays associated with queue development.⁸ However,

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Dixon, Karen K. and Hummer, Joseph E., Capacity and Delay in Major Freeway Construction Zones, Center for Transportation Engineering Studies, North Carolina State

from numerous travels along I-75 and through various ongoing construction project zones, a definite trend was evident in driver behavior. Within extended construction zones such as existed along I-75 between Gainesville and Ocala, FL, traffic would slow briefly (5-10 m.p.h.) upon entering the zone. Then, if there was little or no construction activity would return to their previous speed. Further south on I-75 a series of bridge projects required the closure of one of two lanes in the immediate vicinity of each bridge. Again, traffic tended to slow approximately 10 m.p.h. as it entered each area. A calculation of the brief delay incurred per vehicle would be approximately:

$$\frac{1 \text{ mi.}}{60 \text{ m.p.h.}} - \frac{1 \text{ mi.}}{70 \text{ m.p.h.}} = 8.6 \text{ sec}$$

Given a volume of 1000 vehicles per hour, the total daily delay would amount to more than 57 vehicle-hours. Like a dripping faucet, the small delays can add up. However, the amount is still considered minimal when compared to delays incurred when demand exceeds capacity.

DETERMINISTIC QUEUING MODEL

The Highway Capacity Manual (1994) recommends deterministic queuing analysis as the standard delay estimation technique for freeway work zones. The method is essentially a graphical procedure with the x-coordinate as time and the y-coordinate as the cumulative number of vehicles (see Fig. 4.1). Both demand and capacity volume curves are graphed where the slope of each curve at time t indicates the demand or

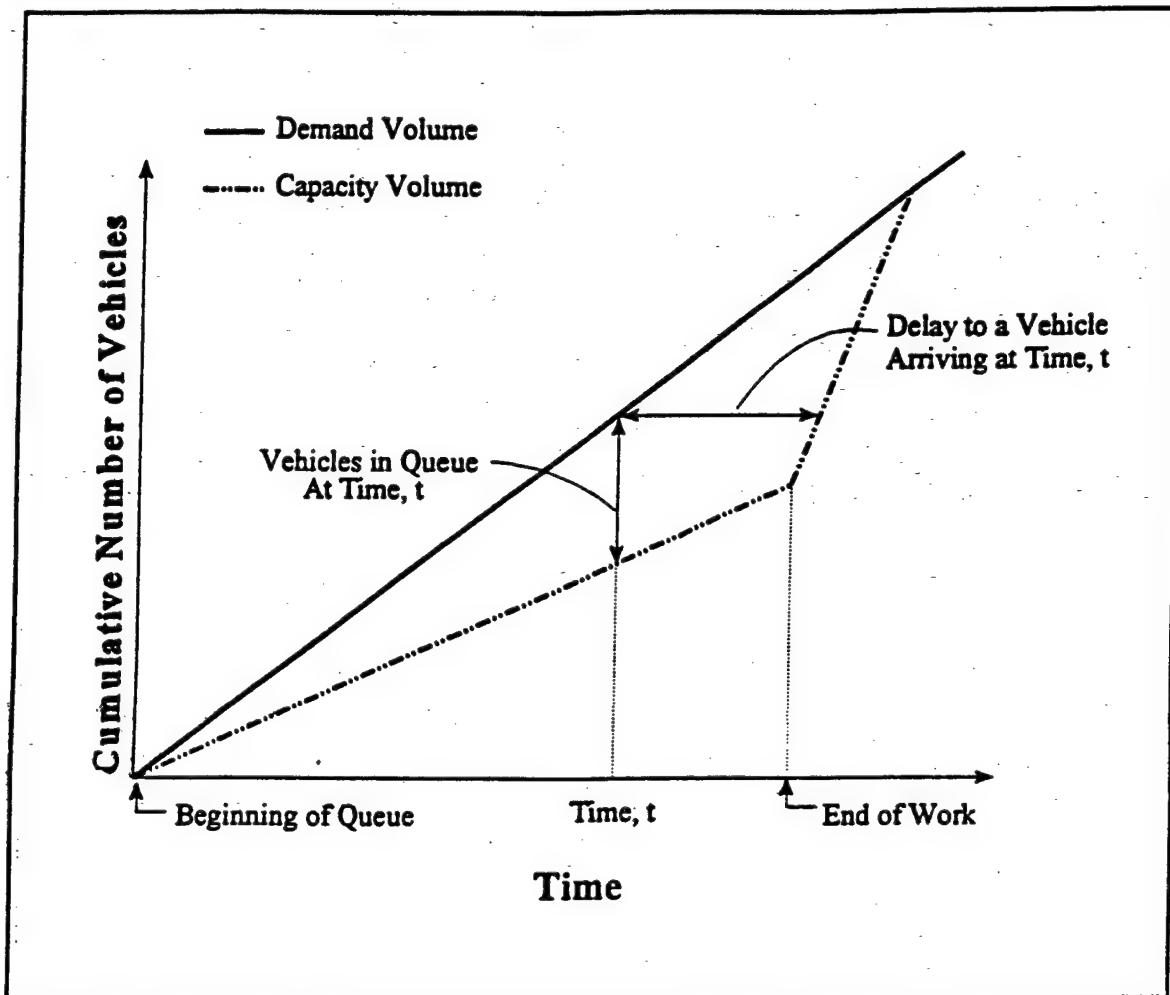


Figure 4.1. Deterministic Queuing Graphical Procedure

capacity at time t . As long as the capacity curve and the demand curve have the same y-coordinate at a given time t , no delay (queue) exists. (In reality, the capacity curve cannot be above the demand curve as excess capacity cannot be "banked" until needed.) When the demand curve exceeds (is higher) the capacity curve then a queue exists. For a vehicle entering the queue at time t , the delay will be the difference between the capacity curve and the demand curve as measured along the x-axis. Likewise, the number of vehicles in the queue at time t will be the difference between the demand curve and the capacity curve measured along the y-axis. Further, the total delays in vehicle-hours between time a and time b will be the area between the curves from $t=a$ to $t=b$.

The following equation from the Highway Capacity Manual (1994) can be used to estimate the length of the queue:

$$D_t = \frac{L_t \times l}{N}$$

where: D_t = estimated queue length at time t (meters),

L_t = estimated number of vehicles in the queue at time t ,

l = average space occupied by a vehicle in the queue (meters), and

N = number of open lanes upstream from the lane closure.

Because the equation equally distributes queue vehicles across all upstream lanes, it does not accurately account for vehicles which merge well before the bottleneck point. If known, a fractional value of N can be used to adjust for this behavior.

The limitation of this method is that it estimates a queue at a single point (at the bottleneck). This translates into the vehicles in the queue being stacked vertically (an impossibility) vice along the length of the road. If considered as queuing horizontally, the method fails to consider the impact approaching vehicles will have on the queue and the behavior of these drivers.⁹

SHOCK WAVE ANALYSIS MODEL

Because of the deterministic models limitations, a new modeling technique was developed to permit the evaluation of flow and density over both space and time. This method is known as "Shock Wave Analysis." In this theory, first proposed by the British researchers in 1955¹⁰, the traffic stream behaves like a fluid. When demand exceeds capacity (see Fig. 4.2), a backward forming shock wave is developed. When the demand and capacity become equal, the shock wave becomes stationary. As demand decreases below capacity, the shock wave moves forward until it dissipates at the bottleneck. The advantage of this model is that if demand continues to increase even while an obstruction is removed and the capacity increases, the backward shock wave will continue while a backward recovery shock wave is also generated from the beginning of the queue.¹¹

⁹

Dixon, Karen K. and Hummer, Joseph E., Capacity and Delay in Major Freeway Construction Zones, Center for Transportation Engineering Studies, North Carolina State University, March 1996, pp. 30-34.

¹⁰

Lighthill, M. J. and Whitman, G. B., "On Kinematic Waves: Part II, A Theory for Long Crowded Roads", Proceedings of the Royal Society, Series A, 229(1178), 1955, pp. 317-345.

¹¹Ibid.

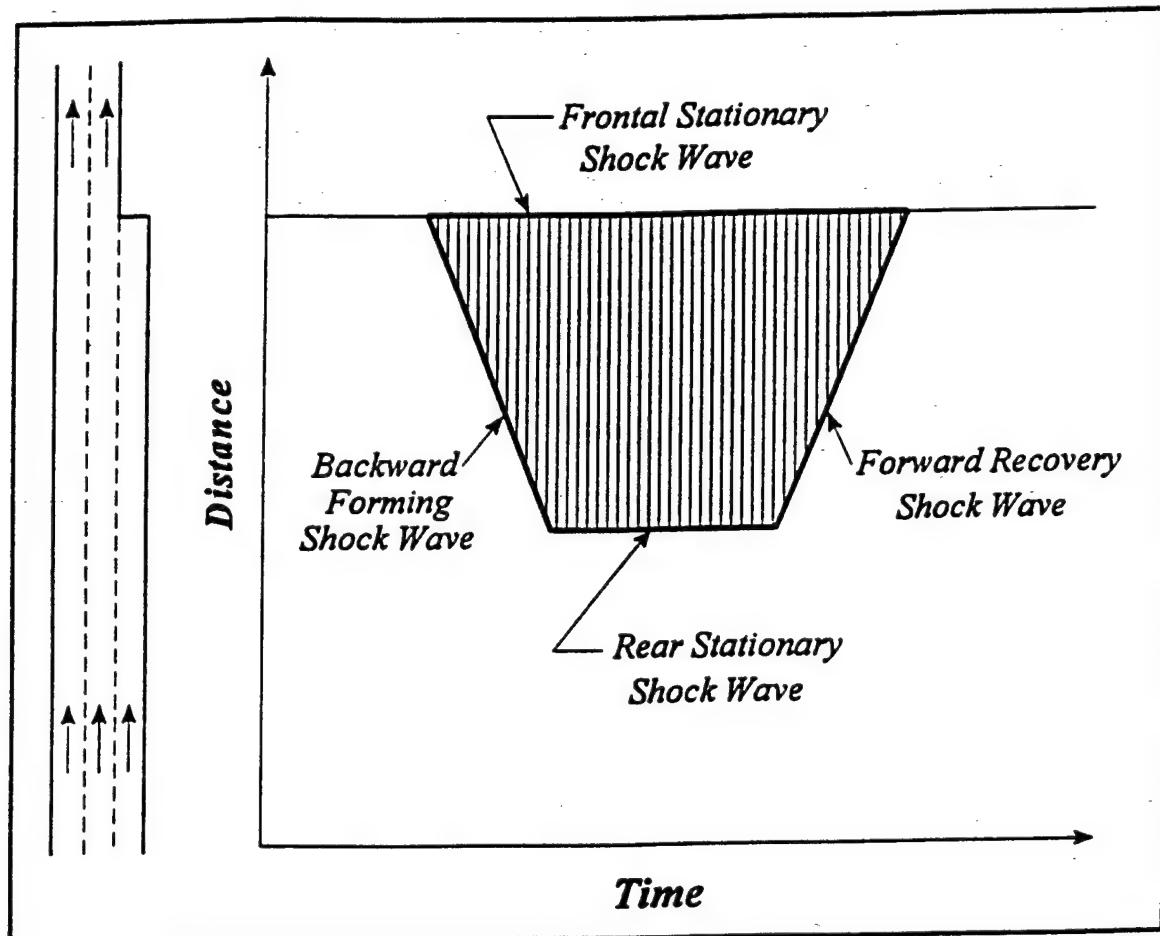


Figure 4.2. Shockwave at Freeway Bottlenecks

An example of this method would be at an urban freeway entrance ramp during rush hour. Vehicles attempting to merge and enter the freeway do not arrive randomly due to a traffic light at the beginning of the ramp. The sudden increase of vehicles trying to merge cause vehicles already on the freeway to slow and merge left to accommodate the incoming vehicles. Once the traffic light changes, no more vehicles (or much fewer) arrive and the freeway traffic stream begins to accelerate. However, a wave of congestion moves backward through the traffic stream followed by the recovery wave (much like a slinky spring).

The basic premise assumes (see Fig. 4.3) that the flow-density relationship is known in three areas: (1) upstream, (2) bottleneck or queued area, and (3) downstream. Given an existing queue at time, T_1 , caused by the demand, Q_1 , exceeding the bottleneck capacity, Q_3 , the area of the queue condition is defined by a density, K_2 , which is the density of the approaching traffic stream to the bottleneck. After a period of time, dt , the queue has become longer. The rate of growth of the shock wave, S , is represented in the following equation:

$$(Q_3 - Q_1) + S(K_1) = S(K_2)$$

or

$$S = \frac{Q_1 - Q_3}{K_1 - K_2}$$

where: S = Speed of Shock Wave (kilometers per hour),

Q_1 = Demand (vehicles per hour),

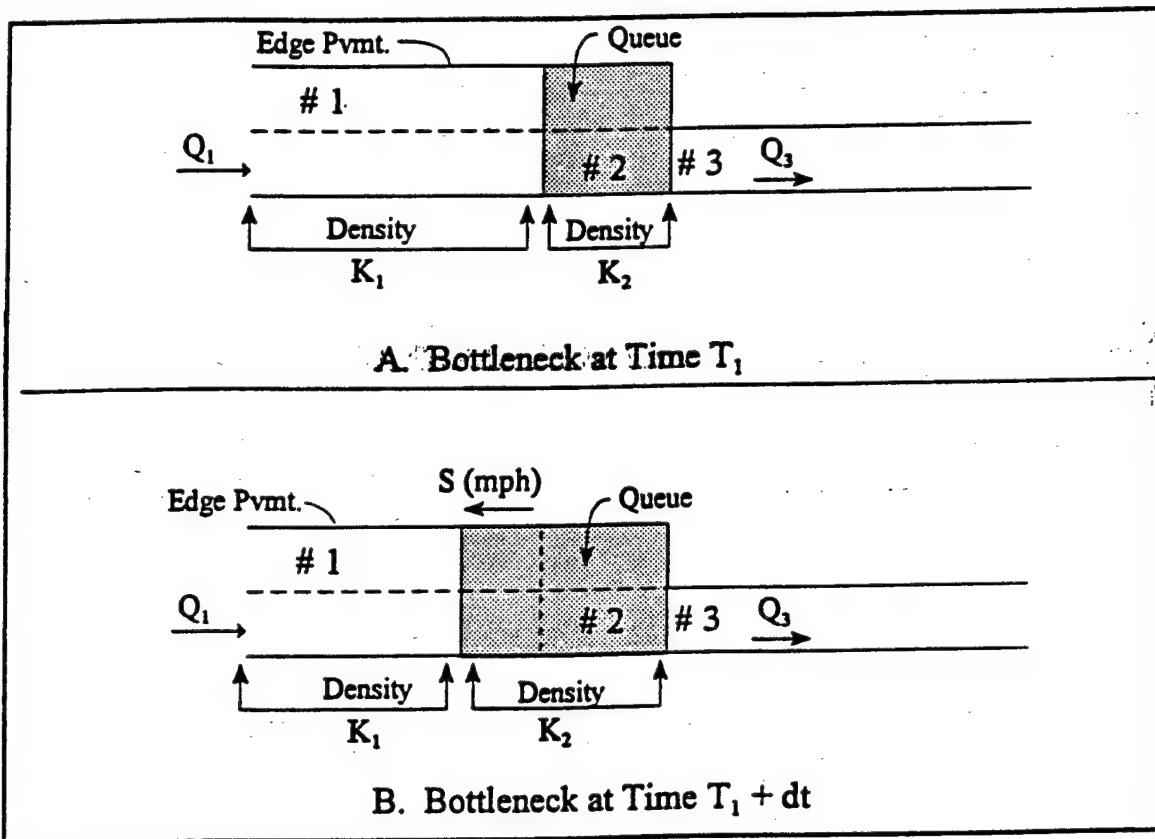


Figure 4.3. Rate of Queue Growth

Q_3 = Bottleneck Capacity (vehicles per hour),

K_1 = Density of approach traffic at Area 1 (vehicles per kilometer per lane),

K_2 = Density in Queue at Area 2 (vehicles per kilometer per lane)

The value of S can be positive or negative. A negative value indicates the shock wave is moving against traffic while a positive value indicates the wave is moving with the traffic.

The queue growth, G , or decay, D , is represented by the same equation. If $S < 0$, then the queue is growing. If $S > 0$, then the queue is decaying.

$$G \text{ or } D = (Q_1 - Q_3) - S(K_1)$$

Determining the number of vehicles in the queue is equal to the cumulative of all queue growth and decay. To calculate the queue length, the equation is as before:

$$D_t = \frac{L_t \times l}{N}$$

The shortcoming of the shock wave analysis method is that it assumes that the bottleneck capacity is a rigid measurable value with easily modeled traffic behavior.¹²

This model can quickly become complicated. In the example used to illustrate the method concerning the rush hour freeway merges, another growth or decay equation

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Dixon, Karen K. and Hummer, Joseph E., Capacity and Delay in Major Freeway Construction Zones, Center for Transportation Engineering Studies, North Carolina State University, March 1996, pp. 34-40.

would be added to account for each wave created by the changing stop light regulating vehicles access to the entrance ramp.

COORDINATE TRANSFORMATION TECHNIQUE MODEL

Originally developed in 1979¹³, the technique is a hybrid of the deterministic queuing model and a steady state statistical queuing method. Under the deterministic queuing model, if demand increases until it becomes equal with the capacity no queue is formed. Unfortunately, real life observations have not held that to be true. Queues do begin forming as the model cannot compensate for behavioral differences in drivers (passive vs. aggressive). The steady state statistical queuing method by itself is unsuitable as a delay model. As the demand approaches capacity, the queue length prediction would become infinite. However, a combination of the two methods can compensate for known deficiencies of each method. Instead of the steady state queue length being asymptotic to the demand to capacity ratio of one, it is shifted to be asymptotic to the deterministic queuing model line (see Fig. 4.4). In this model the demand to capacity ratio is known as the intensity, X .

Continued research over the years has added the refinement of a delay parameter, J_A , used to indicate the magnitude of delay causes along different types of roads. A freeway with few obstructions or bumps would be 0.1. Dirt roads with lots of stop signs would be much higher. From these refinements, the steady state travel time equation is:

¹³

Kimber, R. H. and Hollis, E. M., Traffic Queues and Delays at Road Junctions, TRRL Laboratory Report LR909, 1979.

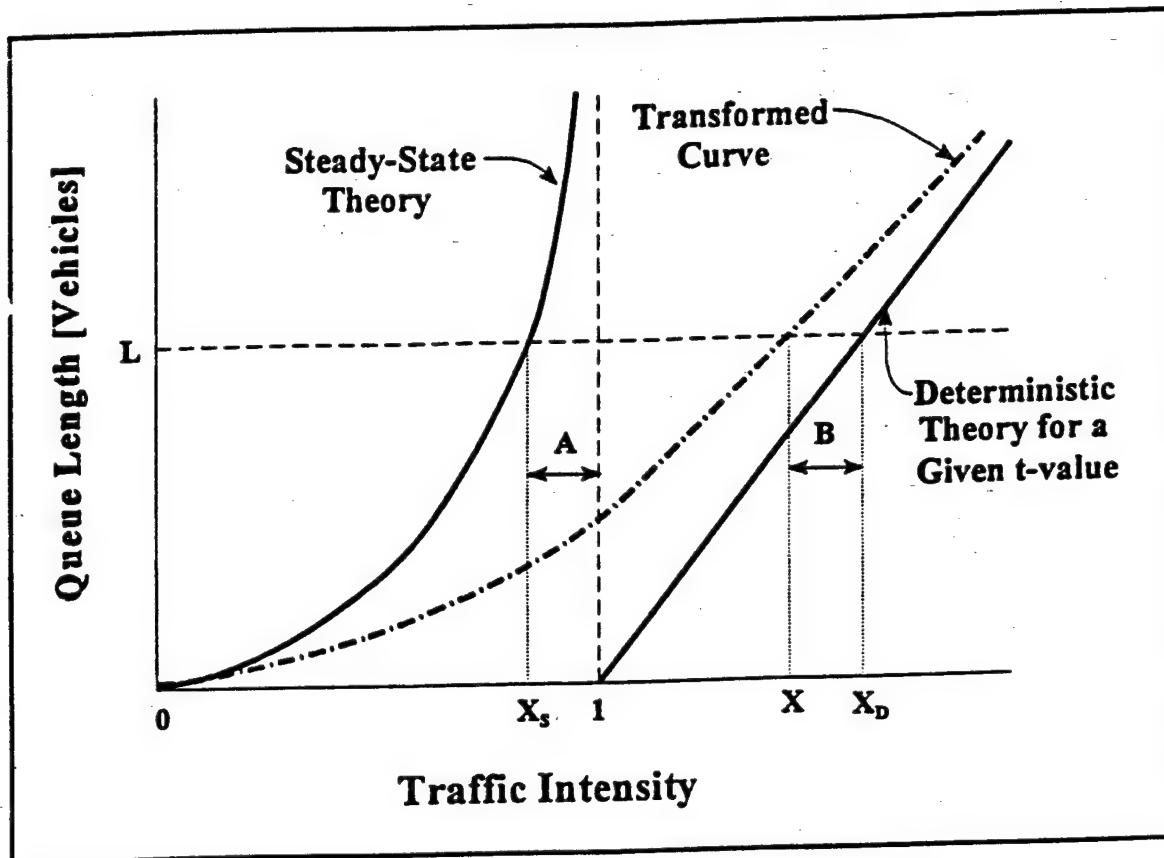


Figure 4.4. Coordinate Transformation

$$t = t_0 + \frac{J_A \times X}{Q \times (1 - X)}$$

where: t = average travel time per unit distance,

t_0 = minimum (zero flow) travel time per unit distance,

J_A = delay parameter (0.1 for freeways),

X = traffic intensity (demand/capacity), and

Q = capacity of vehicles per unit of time.

When first developed, it was found that the steady state delay per unit of time was equivalent to the number of vehicles in the queue. Hence, the equation becomes:

$$L = \frac{J_A \times X_s}{Q \times (1 - X_s)}$$

where: L = queue length (vehicles) per unit time

X_s = steady state traffic intensity, and

all other variables remain the same. This equation assumes random arrivals and service conditions.

The deterministic queue length simply starts with the existing queue, L_0 , adds the demand, q , for the specified time interval, t_f and subtracts the capacity (those passing through the bottleneck), Q , for the same specified time interval. The resulting equation is:

$$L = (q - Q)t_f + L_0$$

Combining the traffic intensity definition, $X_D = q/Q$, with the above, the equation becomes:

$$L = (X_D - 1)Qt_f + L_0$$

The time dependent queue length based on the assumption that the transformed curve is the same distance from the deterministic line as the steady state theory curve is from X (intensity) = 1 ($A = B$ in Fig. 4.4). The following equation results:

$$1 - X_S = X_D - X$$

where: X = intensity of the transformed, time dependent equation.

Solving for X_S , the equation becomes:

$$X_S = X - (X_D - 1)$$

Substituting the deterministic queue length with the traffic intensity equation into the previous results in another definition of X_S :

$$X_S = X - \frac{(L - L_0)}{(Q \times t_f)}$$

One final substitution of the previous equation into the steady state delay term equation yields:

$$\left(\frac{Q}{J_A}\right)L^2 + \left[\frac{Q^2 t_f}{J_A}(1 - X) - \frac{L_0 Q}{J_A} + 1\right]L - (XQt_f + L_0) = 0$$

Solving for L using the quadratic formula, the time dependent queue length equation is:

$$L = \frac{-b + \sqrt{b^2 - 4ac}}{2a}$$

where:

$$a = \frac{Q}{J_A},$$

$$b = \frac{Q^2 t_f}{J_A} (1 - X) - \frac{L_0 Q}{J_A} + 1, \text{ and}$$

$$c = -X Q t_f - L_0.$$

The coordinate transformation technique is a compromise technique. Additional calibrations of the J_A factor may be warranted.¹⁴

QUEUE LENGTH

Each of the three previous models computes the number of vehicles in the queue. As mentioned previously, to determine the length of the queue, the number of open lanes upstream of the bottleneck and the average space per vehicle must be known. Per the Highway Capacity Manual (1994), the proper lanes would be equal to two and the

¹⁴

Dixon, Karen K. and Hummer, Joseph E., Capacity and Delay in Major Freeway Construction Zones, Center for Transportation Engineering Studies, North Carolina State University, March 1996, pp. 40-45.

average space for a queue vehicle is given as 12 meters. As part of the data collection, information was obtained to verify the spacing. Devices were placed at 853 meters, 2073 meters and two at 5060 meters to record individual vehicle speed and time when a specific spot was reached. The first two locations were downstream of warning signs while the farthest devices were upstream of the construction warning signs.

The actual data collected indicate a range of space headway data from 21.5 meters to 47.2 meters for queued conditions downstream of the lane closure sign. The averages were 35, 35 and 39 meters for all sites. The larger gaps occurred in the lane to be closed. Upstream of the warning sign the space headway data average 17.4 meters. In all cases, the observed amount of space headway was significantly higher than the 12 meters recommended by the Highway Capacity Manual (1994). To ensure an accurate evaluation between the observed data and the estimated data from the three models (see Fig. 4.5), the observed headway data (average vehicle spacing) were used for calculating queue length in the models. The values were 40 meters for queued conditions prior to the lane closure sign and 18 meters for queued conditions upstream of the sign.¹⁵

¹⁵

Dixon, Karen K. and Hummer, Joseph E., Capacity and Delay in Major Freeway Construction Zones, Center for Transportation Engineering Studies, North Carolina State University, March 1996, pp. 77-85.

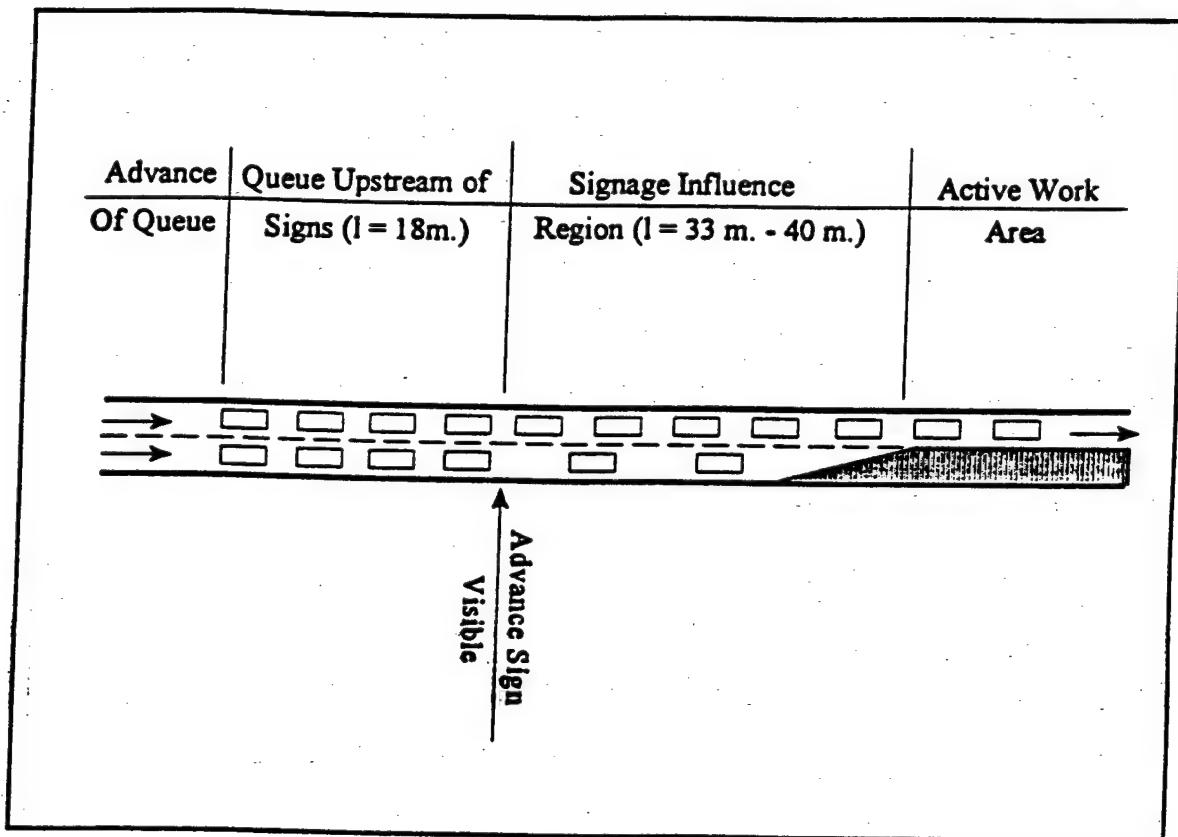


Figure 4.5. Queued Density Regions

RESULTS

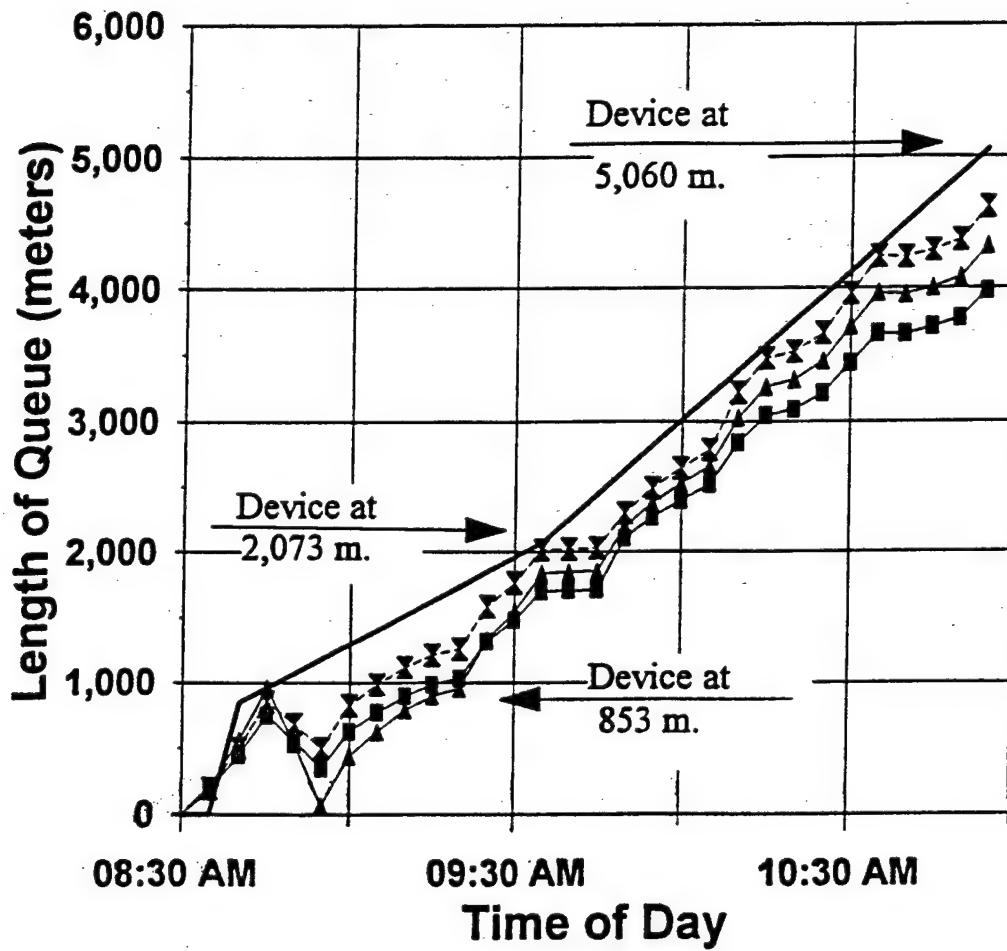
A graphical review of the test results indicates that all the models generally underestimated the actual queue (see Figs. 4.6, 4.7, 4.8) However, of the three the coordinate transformed approach came closest to reaching the actual observed queue length. The deterministic and shock wave approach both overestimated the decay observed around 10:30 a.m. The coordinate transformed performed better in this area. Overall, the coordinated transformed approach provided the most accurate approach.

An interesting observation made by the data collectors was the apparent unique behavior of heavy vehicles within the traffic stream. The trucks exhibited a pacing behavior which appeared to control the queue operating speed.¹⁶ This information would appear to corroborate some of the observations of the data in the I-75 lane closure project. Such better understanding of truck driver behavior may lead to improved passenger car equivalencies based on the percent of trucks in the traffic stream.

Areas of concern which require additional study include determination of proper headway values. It appears that the average spacing in the queue is being seriously underestimated.

¹⁶Ibid., p. 108.

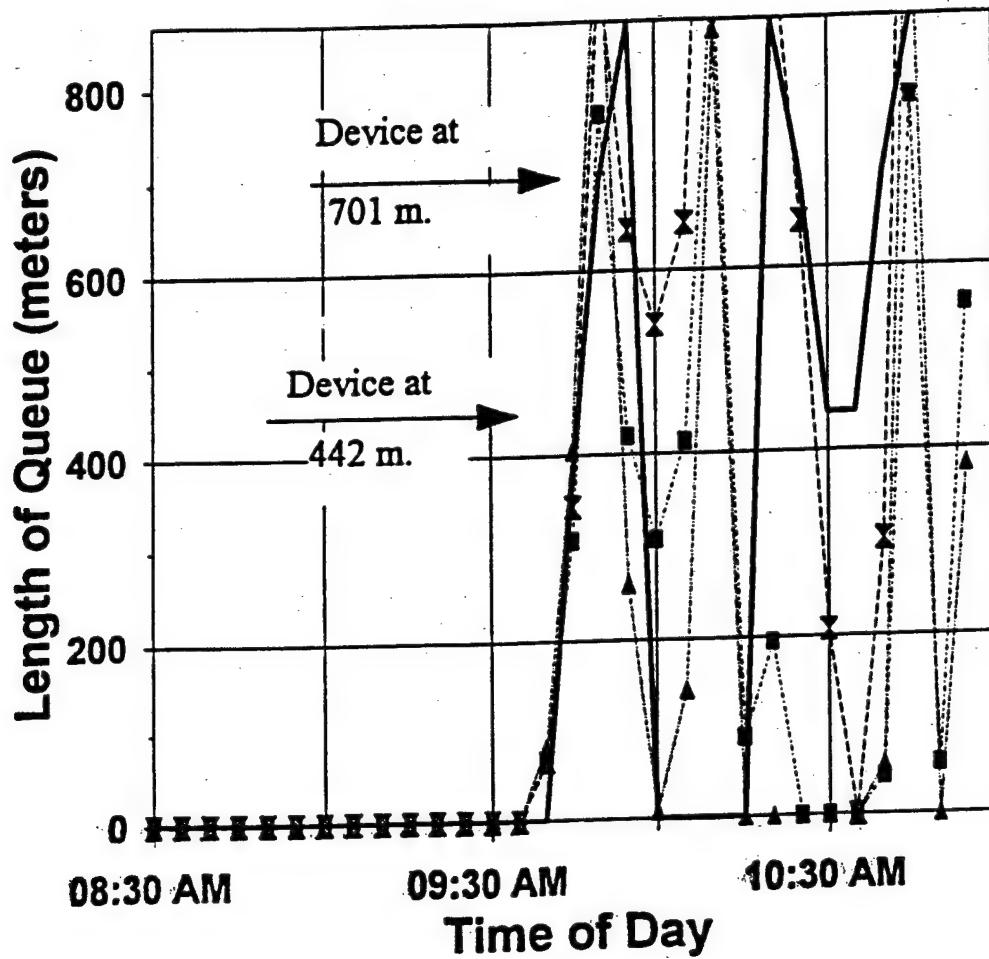
**Flow Rate of 1076 vph
in Queue Assumed**



— Observed	■ Deterministic
★ Shock Wave	-x- Coord. Transformed

Figure 4.6. Site 21 - Delay Analysis Comparison

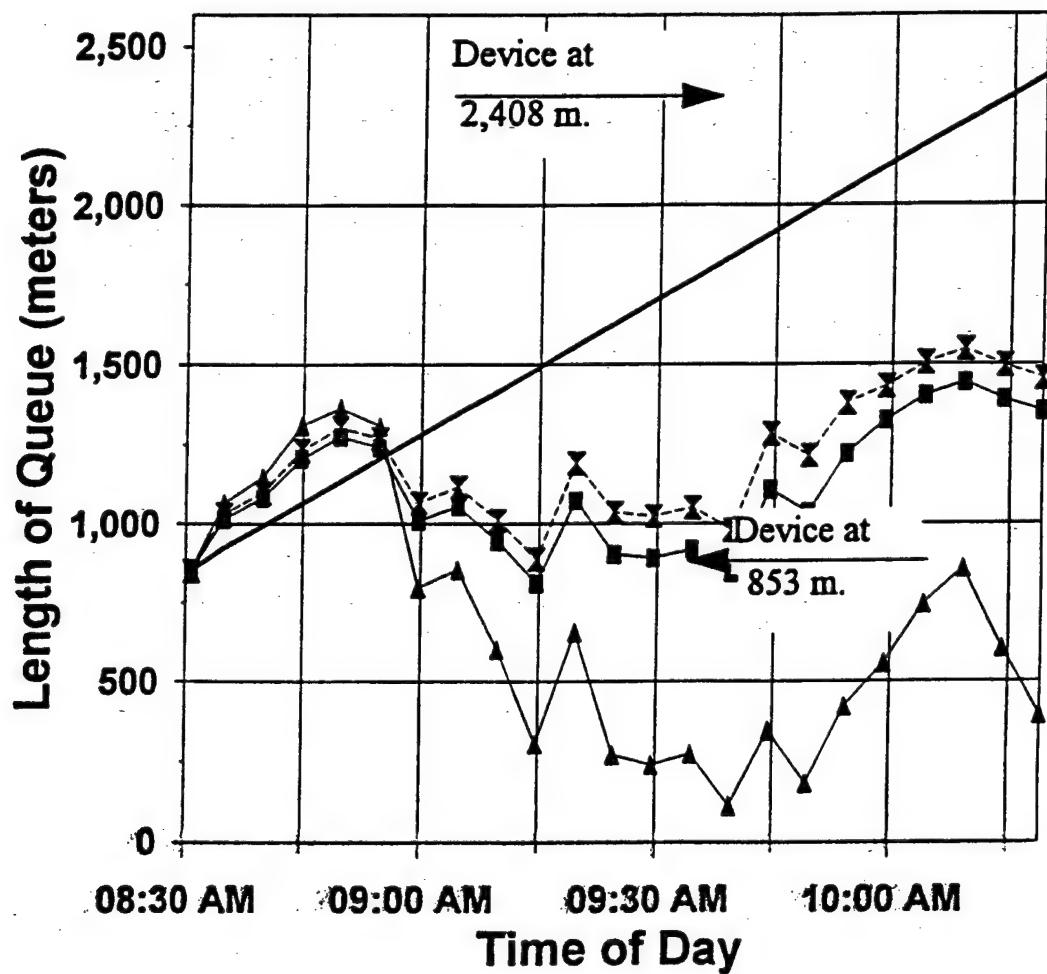
**Flow Rate of 1076 vph
in Queue Assumed**



— Observed	--- Deterministic
→ Shock Wave	---x--- Coord. Transformed

Figure 4.7. Site 18 - Delay Analysis Comparison

**Flow Rate of 1076 vph
in Queue Assumed**



— Observed	■ Deterministic
▲ Shock Wave	-x- Coord. Transformed

Figure 4.8. Site 20 - Delay Analysis Comparison

CHAPTER 5 - QUEWZ-92

Over the years several models have been developed using the deterministic model with additional parameters added to improve the accuracy of the estimations generated. The most well known computer program using this method is the Queue and User Cost Evaluation of Work Zones (QUEWZ) first developed in 1980. The program has undergone several revisions over the years. The most known recent version is the QUEWZ-92 version.

The QUEWZ program is based on the deterministic queuing model. The inaccuracies of the model were demonstrated previously. Additionally, the North Carolina Department of Transportation has repeatedly observed that actual data is inconsistent with QUEWZ queue length results and the Highway Capacity Manual's (1994) capacity values.¹⁷

This update included a more comprehensive database and improved procedures for estimating the travel impacts of freeway maintenance and reconstruction projects. The database included data collected from projects mostly located in Texas (55 out of 61). The projects included both major reconstruction projects, short term projects, and accident statistics.

¹⁷

Dixon, Karen K. and Hummer, Joseph E., Capacity and Delay in Major Freeway Construction Zones, Center for Transportation Engineering Studies, North Carolina State University, March 1996, p. 2.

Enhancements include output options for estimating road user costs and estimating the effects of different lane closure options, speed and queue estimation, and a diversion algorithm. The speed and queue estimation procedures are based on the procedures available in the Highway Capacity Manual (1985) which has been replaced by the 1994 version. The road user costs include vehicle operating costs and delay costs but do not detail which costs are included. The diversion algorithm is used with the road user cost option to provide an estimate of costs associated with those drivers who choose to seek alternate routes to avoid the construction zone. All user costs are in 1990 dollars though a cost update factor exists to permit the entering of Consumer Price Index data to bring the estimates to the current year.

As with prior QUEWZ, this version primarily uses traffic volume data from both urban and rural areas in Texas.¹⁸ This creates a problem with using the program outside of Texas. The Texas highway system has an extensive network of frontage roads that permit vehicles to easily bypass congested areas. Such a system easily influences driver behavior to use these frontage roads because of their close proximity. Because most highway systems in other states do not have this feature, the estimates produced may be skewed.¹⁹ Particularly with the diversion algorithm, the program will most likely estimate

18

Krammes, Raymond A., et. al., Traffic Pattern Assessment and Road User Delay Costs Resulting from Roadway Construction Options, Texas Transportation Institute, College Station, TX, 1993.

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Dixon, Karen K. and Hummer, Joseph E., Capacity and Delay in Major Freeway Construction Zones, Center for Transportation Engineering Studies, North Carolina State University, March 1996, pp. 1-2.

a higher number of diversions at a lower cost per diverted vehicle than experienced in states without extensive frontage roads.

Based on the validation testing of the deterministic queuing model reviewed previously, the modeling methods of this program appear highly suspect for use anywhere. While extensive research and redevelopment may improve the adjustment factors, one must be very skeptical that the basic premise for the model development is sound. With the advancements that continue to be made in computer speed, miniaturization, and user friendly interfaces, it may be more advantageous to start from scratch and develop a new model that better predicts actual observations.

CHAPTER 6 - HERS

The Highway Economic Requirements System (HERS) 2.0 is a comprehensive road management system being developed under the auspices of the Federal Highway Administration. A review of the simplified model of the system indicates it will have the capability to forecast traffic growth and pavement condition, identify unacceptable conditions, determine the most cost effective correction method, select the improvements needed, perform cost/benefit analysis, and even determine pavement thickness needs for resurfacing and new construction. While most of these items are outside the scope of the project, there is one area of particular applicability to this report. That being road user cost data and development. The model establishes a weighted average of road user costs based on the seven vehicle types.

The first items included in the model are costs for on-the-clock trips. Costs included are labor plus fringe benefits, costs related to vehicle productivity, inventory carrying costs, and spoilage costs. Labor costs are based on the prevailing wages supplied by the Department of Labor and average vehicle occupancy. Vehicle costs are per hour are determined by computing the average cost per year assuming a five-year life span. Inventory and spoilage costs reflect the time value of goods of goods being carried by trucks.

Further items are other trips or off-the-clock trips. The value of time was calculated in the same manner as above except that wage data were not used. Instead, several studies were done to survey drivers and riders to determine the value of their time

when traveling. The results show approximately a 55 to 60 percent of the prevailing labor rate was adequate for the driver while passengers reported valuations of 45 percent of the normal wage rate. Additionally, this amount is increased when waiting is required (such as in a stop light) by 1.5 to 2.0. When traveling in congested traffic, survey results show a 30 to 50 percent increase in the value of time.

Vehicle operation costs are the next items evaluated. Costs were identified as constant-speed operating costs which include parameters for road conditions, excess operating costs for speed-change cycles, and excess operating costs for curves.

The final items are safety costs. The model incorporates crash, injury, and fatality data based on type of roadway supplied by the National Safety Council. The value of reducing injuries and fatalities is based on a "willingness to pay" approach which reflects what people have been willing to spend on small safety improvements. Property damage and injury cost are based on actual costs. Estimating the value of a death averted is based on the value people put on mortality reductions as evidenced by the amount people are willing to pay to increase their health and safety, and wage differentials to encourage people to take riskier jobs.²⁰

This model is excellent to develop road user costs. The total costs, except for safety costs, are provided as hourly rates which make calculation simple since all of the delay models determined delay estimates can be converted easily to total vehicle-hours of

²⁰

U.S. Department of Transportation, Federal Highway Administration, Highway Economic Requirements System, Volume IV: Technical Report, National Level, Version 2, November 1996, pp.8-27 to 8-54.

delay and multiplied by the hourly cost data based on the observed vehicle types in the traffic stream. Safety costs are listed as a cost per occurrence though sufficient data are provided to determine the risk of an accident on a particular road based on road type and the average annual daily traffic. Costs can be adjusted using the Consumer Price Index.

**Table 6.1. Weighted Average Value of One Hour Travel Time by Vehicle Type
(1993 Dollars)**

Auto	4-Tire Truck	6-Tire Truck	3-4 Axle Truck	4-Axle Comb.	5-Axle Comb.
\$11.12	\$12.61	\$23.69	\$27.07	\$30.09	\$30.26

Source: HERS, Volume IV: Technical Report

Table 6.2. Average Cost of Accidents (1993 Dollars)

Functional System	Cost per Nonfatal Injury	Property Damage Cost per Crash
Urban		
Interstate	\$26,100	\$6,000
Other Freeway	\$21,750	\$7,200
Other Principal Arterial	\$23,200	\$7,200
Minor Arterial	\$18,850	\$7,200
Collector	\$14,500	\$6,000
Rural		
Interstate	\$24,650	\$4,800
Other Principal Arterial	\$31,900	\$6,000
Minor Arterial	\$26,100	\$6,000
Major Collector	\$36,250	\$6,000
Minor Collector	\$29,000	\$4,800

Source: HERS, Volume IV: Technical Report

Estimated Benefit for each Death Averted (1993 Dollars): \$2,500,000

CHAPTER 7 - CONCLUSION

The need to determine road user costs continues to grow in importance. User costs can help project managers make good business decisions on where to invest limited funds, be used to determine liquidated damages or lane rental fees, and develop improved traffic management plans. The ability to be successful is highly dependent on the validity of the model used to determine the estimate.

Accurate road user cost estimates can be useful in determining fair and reasonable rates for lane rentals and liquidated damages. Contractors will challenge the assessment of these fees if it is in their best interest to do so. They perform the same cost/benefit analysis that a government project manager should. In order for the rates to not be considered punitive, the government must show through reliable data how the lane rental fees or liquidated damages were determined. Using the same amount for every project is no longer acceptable since the impact to users in different locations will not be the same.

Traffic management plans are essential to reduce road user costs during construction projects. While efforts are continuing to be made to quantify these costs more accurately, simply passing these costs on to contractors through lane rental fees, liquidated damages or other method may be difficult to enforce without a traffic management plan. From my own experience in managing construction projects and legal precedence, owners of construction projects can be liable for contractor costs associated with the owner's actions or inactions. The failure of project managers to take prudent measures to mitigate user costs, can deny the owner's ability to recoup these costs from the contractor.

It should be noted that traffic management plans differ between the urban and rural environment. In the rural environment the effort should be on improving the flow of vehicles (capacity) through the construction zone. For most cases in rural areas, the access to alternate routes are limited. Additionally, the Average Daily Traffic will remain fairly consistent with non-construction periods. In the urban environment, trips are generally shorter, the trips generally originate and end within close proximity with other trips (commuter), and alternate routes through the corridor are more readily available. In all situations, it is recommended to pay particular attention to work site layout concerning traffic control device types and placement and sight distance to the lane closure point.

In urban areas, the traffic management plan should be focused on moving people vice vehicles through the construction zone. With this focus, the traffic management plan can have a more positive impact on changing a commuter's desire to use mass transit systems.

Upon review of urban reconstruction projects, it is clearly difficult to convince commuters to change their mode of transportation from their automobile. While the traffic management plan was excellent and comprehensive, the failure to increase mass transit ridership can be attributed to the outstanding planning for handling vehicle volumes on the expressway and via alternate routes. As long as commuters can complete personally owned vehicle trips with no or little noticeable change in travel times and faster than by mass transit methods, it will be extremely difficult to change their behavior. Unfortunately, the ability to succeed in this regard will be heavily dependent upon the traffic management committee's political astuteness and their positive, professional relationship with the elected officials, media representatives, and the commuting public.

Consideration of user costs in traffic management plans can provide new insights into actions that need to be taken. Specifically, through the estimation of the impact costs to users, construction schedules can be altered to improve the cost/benefit ratio. As with any disruptive construction project, the contractor is concerned about schedule impacts which can cost him time and money. Determining the contractor's cost has always been much easier than the impact costs on the public. Consequently, the public is usually bears the bulk of the inconvenience costs. In addition, the public also bears the cost of improvement costs for facilities which are then not used or rarely used in relation to the costs. The desire to fund the numerous ideas which come out of a traffic management plan meeting must be tempered by good business sense an honest look at the cost/benefit or payback period. The ability to accurately estimate the user's cost with confidence will be a major step in developing least cost solutions. More and more, government project managers are being asked to think like private business and make good business decisions in the management of publicly funded projects. However, for leaders to make sound business decisions, they must first have sound information to rely on.

The various models reviewed all needed additional adjustments to improve their reliability. Particularly disheartening, is that the model used by most State Departments of Transportation is consistently lacking in its accuracy. One of the difficult problems with any model is that once the developer gets it right, the environment or trend has changed and the model becomes invalid. As an example, much of the data on the percentage breakdown of vehicle types used in modeling what is on the road are several years old. This data would reflect a vehicle fleet when the trend was for smaller, and

more fuel efficient cars. Today, the trend is toward large sport utility vehicles. The predominance of these larger vehicles can result in congestion problems where existing models cannot predict the problem.

Technology may be able to provide a solution to this problem. The day when these studies required large number of human observers is quickly fading away. New methods exist to collect raw data and even process it automatically. Current models need to have current data in order to be effective and accurate. Therefore, it would be beneficial to develop the means to collect data continuously, both at selected permanent sites (such as the ADT counters embedded in freeways) and at construction sites to continuously improve the database information used to develop the necessary estimating models.

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